



Impact of inclination angle on thermo-bioconvection of nanofluid containing gyrotactic microorganisms saturated in porous square cavity

J. Bodduna^{}, C.S. Balla^{*},^{} and M.P. Mallesh

Abstract

This paper focuses on the result of inclined angle on bioconvection of porous media bounded by cavity wall square enclosure filled with both nanofluid and gyrotactic microorganisms passing through the media with pores. The dimensionless velocity, temperature, concentration, and mass transformation equations are solved by using the weighted residual Galerkin's finite element method. The result of the inclination angle from $\delta = 0^\circ$ to $\delta = 180^\circ$ in a square cavity is interpreted. The outcomes of inclination on various key parameters, such as Rayleigh number, bioconvective Rayleigh number, Peclet number, Brownian motion, and the ratio of buoyancy, are discussed. Furthermore, the mean Nusselt number, Sherwood number, and density number are discussed at vertical walls.

AMS subject classifications (2020): Primary

Keywords: Nanofluid, Inclination angle, Buoyancy ratio, Peclet number, Square cavity, Bioconvection.

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1 Introduction

The present problem is dealing with the nanofluid flow through the porous square cavity with temperature difference, which has a wide range of applications in recent years, such as geophysics, geothermal energy utilization, and many technologies. The bioconvection of the nanofluid containing gyrotactic microorganisms has a wide range of practical applications, such as chemical catalytic converters, buried electronic cables, pollutant dispersion in aquifers, food industrial forms, and so on. These types of many areas of applications are documented in these references [10, 24, 14, 15, 31].

The properties and utilization of the nanofluid were first introduced by Choi and Eastman [11] at ASME annual meeting. Many people have described the properties of nanofluids, such as [13, 30, 24, 23, 26]. In many electronic devices, like computers, boilers, converters, and so on, the angle of inclination to the surface affects the gravity force on the fluid, temperature gradient, and velocity of the fluid flow. In [32], the author expressed the free convection of the composite wall enclosure. Kuyper et al. [20] studied the effect of inclined angle on different flows in square cavity walls. Kuznetsov [21] explained the microscopic convection motion of the oxytactic microorganisms due to the temperature effect. Shermet and Pop [28] expressed that the result of the thermal movement of microorganisms in the nanofluid having gyrotactic microorganisms is a closed porous square cavity. Aziz, Khan, and Pop [5] presented the flow behavior of the nanofluid with gyrotactic microorganisms on a flat plate. At viscous dissipation, the behavior of oxytactic microorganisms in porous square cavities was discussed [2, 3]. Jamuna and Balla [17] discussed the behavior of the heat source and sink of the gyrotactic microorganisms in the square cavity. The activation energy effect on the gyrotactic microorganisms was discussed in [18]. The influence of Soret and Dufour on free convection of the fluid flow in the inclined four-side closed walls was explained in [8]. The MHD double-diffusion in the porous square enclosure with radiation and chemical reaction and the outcome inclination of the porous square cavity filled with gyrotactic microorganisms with the heat transformation was discussed in [6, 7]. Nanofluid movement in an inclined square cavity with gyrotactic microorganisms at MHD free convection was reported in [27].

The effect of angle movement of the square adiabatic wall on mixed convection of the nanofluid was explored in [16]. Aounallah et al. [4] explained the turbulent flow behavior of the nanofluid in an inclined square cavity on free convection, and Sheremet, Grosan, and Pop [27] investigated the free convective flow of nanofluid in inclined four-sided chamber with gyrotactic microorganisms. Tsai, Li, and Lin [29] discussed the inclination of the plate shield, and Aboueian-Jahromi, Hossein Nezhad, and Behzadmehr [1] studied the steady flow in inclined cylinders.

Rajarithinam and Nithyadevi [25] examined the movement of Cu-water nanofluid in inclined cavity walls with pores. The thermosolutal Maragoni

effects of the bioconvective fluid flow with gyrotactic microorganisms on inclined sheets were explained in [19]. Recently, Varol, Oztop, and Koca [34] explained different fluids' laminar flow in the different inclined enclosures.

Since, from the above literature survey, we note that many authors concentrated on the inclined angle of different geometries with convection of nanofluid with gyrotactic microorganisms. The novelty of this paper contains the square-shaped cavity enclosure with fluid containing nanoparticles and gyrotactic microorganisms. Galerkin's finite-element method is used to solve the nondimensional governing equations.

2 Mathematical modeling

We consider the bioconvection flow in an inclined two-dimensional porous four-sided square cavity of dimension L containing nanofluid with gyrotactic microorganisms. Let us assume that δ is the inclination angle of the cavity wall with the horizontal surface. The vertical walls are maintained in various temperatures T_C and T_H , respectively ($T_H > T_C$). The remaining walls were kept perfectly insulated. The direction of gravity force g acts opposite to the vertical axis (Y-axis).

The steady-state Darcy–Boussinesq approximation governing equations are

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \quad (1)$$

$$\frac{\mu}{k}u = -\frac{\partial p}{\partial x} - [(\rho_p - \rho_f)(C - C_{\min}) - (1 - C_{\min})\rho_f\beta(T - T_C) + \gamma n\Delta\rho]g \sin \delta, \quad (2)$$

$$\frac{\mu}{k}v = -\frac{\partial p}{\partial y} - [(\rho_p - \rho_f)(C - C_{\min}) - (1 - C_{\min})\rho_f\beta(T - T_C) + \gamma n\Delta\rho]g \cos \delta, \quad (3)$$

$$\begin{aligned} u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = & \alpha_m \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \tau D_B \left(\frac{\partial C}{\partial x} \frac{\partial T}{\partial x} + \frac{\partial C}{\partial y} \frac{\partial T}{\partial y} \right) \\ & + \frac{\tau D_T}{T_C} \left[\left(\frac{\partial T}{\partial x} \right)^2 + \left(\frac{\partial T}{\partial y} \right)^2 \right], \end{aligned} \quad (4)$$

$$u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D_m \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) + \frac{D_T}{T_c} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right), \quad (5)$$

$$\frac{\partial}{\partial x} (un + \tilde{u}n - D_n \frac{\partial n}{\partial x}) + \frac{\partial}{\partial y} (vn + \tilde{v}n - D_n \frac{\partial n}{\partial y}) = 0. \quad (6)$$

Here γ is the mean volume for microorganisms, $\Delta\rho = \rho_{cell} - \rho_f$ is the density difference of cell, T_C is the cold wall temperature, T_H is the hot wall temperature, α_m is porous medium thermal diffusivity, C is the concentration of nanoparticles, C_0 is nanoparticles average density, $C_{\min}$ is minimum concentration of oxygen essential for microorganisms, C_p is specific heat at

constant pressure, D_n is microorganisms diffusion coefficient, D_B is the Brownian diffusion constant, D_T is the thermophoretic diffusion coefficient, n is motile density number of microorganisms, g is the gravity force, chemotaxis constant is b , and the maximum speed of cell swims is w_C . The average swimming velocities of microorganisms are $\tilde{u}$ and $\tilde{v}$ given as

$$\tilde{u} = \frac{bw_C}{\Delta C} \frac{\partial C}{\partial x}, \quad \tilde{v} = \frac{bw_C}{\Delta C} \frac{\partial C}{\partial y}. \quad (7)$$

Consider dimensional stream function ψ . Then u and v in x and y directions are considered as $u = \frac{\partial \psi}{\partial y}$ and $v = \frac{\partial \psi}{\partial x}$ by introducing the boundedless variables $X = \frac{x}{H}$, $Y = \frac{y}{H}$, $\Psi = \frac{\psi}{\alpha_m}$, $\theta = \frac{T-T_C}{T_H-T_C}$, $\phi = \frac{C-C_{\min}}{\Delta C}$, and $N = \frac{n}{n_0}$, where n_0 is the microorganism averaged density.

Substituting above unbounded variables into equation (1)–(7), then we get the following partial differential equations:

$$\begin{aligned} \frac{\partial^2 \Psi}{\partial X^2} + \frac{\partial^2 \Psi}{\partial Y^2} = & RaNr \left(\frac{\partial \phi}{\partial X} \cos \delta - \frac{\partial \phi}{\partial Y} \sin \delta \right) - Ra \left(\frac{\partial \theta}{\partial X} \cos \delta - \frac{\partial \theta}{\partial Y} \sin \delta \right) \\ & + RaRb \left(\frac{\partial N}{\partial X} \cos \delta - \frac{\partial N}{\partial Y} \sin \delta \right), \end{aligned} \quad (8)$$

$$\begin{aligned} \left(\frac{\partial \Psi}{\partial Y} \frac{\partial \theta}{\partial X} - \frac{\partial \Psi}{\partial X} \frac{\partial \theta}{\partial Y} \right) = & \left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} \right) + Nb \left(\frac{\partial \phi}{\partial X} \frac{\partial \theta}{\partial X} + \frac{\partial \phi}{\partial Y} \frac{\partial \theta}{\partial Y} \right) \\ & + Nt \left[\left(\frac{\partial \theta}{\partial X} \right)^2 + \left(\frac{\partial \theta}{\partial Y} \right)^2 \right], \end{aligned} \quad (9)$$

$$Le \left(\frac{\partial \Psi}{\partial Y} \frac{\partial \phi}{\partial X} - \frac{\partial \Psi}{\partial X} \frac{\partial \phi}{\partial Y} \right) = \frac{\partial^2 \phi}{\partial X^2} + \frac{\partial^2 \phi}{\partial Y^2} + \frac{Nt}{Nb} \left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} \right), \quad (10)$$

$$\frac{\partial \Psi}{\partial X} \frac{\partial N}{\partial Y} - \frac{\partial \Psi}{\partial Y} \frac{\partial N}{\partial X} + \frac{PrPe}{Sc} \left(\frac{\partial^2 \phi}{\partial X^2} + \frac{\partial^2 \phi}{\partial Y^2} \right) = \frac{Pr}{Sc} \left(\frac{\partial^2 N}{\partial X^2} + \frac{\partial^2 N}{\partial Y^2} \right), \quad (11)$$

where $Ra = \frac{gK\beta(1-C_0)\Delta TL}{v\alpha_m}$, $Rb = \frac{\gamma\Delta\rho n_0}{\rho_f\beta(1-C_0)\Delta T}$, $Le = \frac{\alpha_m}{D_B}$, $Pe = \frac{bw_C}{D_n}$, $Nb = \frac{\tau D_B \Delta C}{\alpha_m}$, $Nt = \frac{\tau D_T (T_H - T_C)}{\alpha_m T_C}$, $Pr = \frac{\mu_f}{\rho_f \alpha_f}$, $Sc = \frac{\mu_f}{\rho_f D_n}$, and $Nr = \frac{(\rho_p - \rho_f)C_0}{\rho_f \beta(1-C_0)\Delta T}$.

The dimensionless form of conditions at boundary is expressed in Figure 1.

We have $\Psi = 0$ for all sides,

$\phi = 1$, $\theta = 1$, $N = 1$ at $X = 0$,

$\phi = 1$, $\theta = 0$, $N = 1$ at $X = 1$,

$\phi = 1$, $\frac{\partial \theta}{\partial Y} = 0$, $Pe.N \frac{\partial \phi}{\partial Y} = \frac{\partial N}{\partial Y}$ at $Y = 0$, and

$$\frac{\partial \phi}{\partial Y} = \frac{\partial \theta}{\partial Y} = \frac{\partial N}{\partial Y} = 0 \quad \text{at } Y = 1.$$

Local solid Nusselt number, Sherwood number of nano particles and Sherwood microorganism are defined as

$$Nu_Y = -\left(\frac{\partial \theta}{\partial X}\right)_{X=0,1}, \quad Sh_Y = -\left(\frac{\partial \phi}{\partial X}\right)_{X=0,1}, \quad \text{and } Nn_Y = -\left(\frac{\partial N}{\partial X}\right)_{X=0,1}.$$

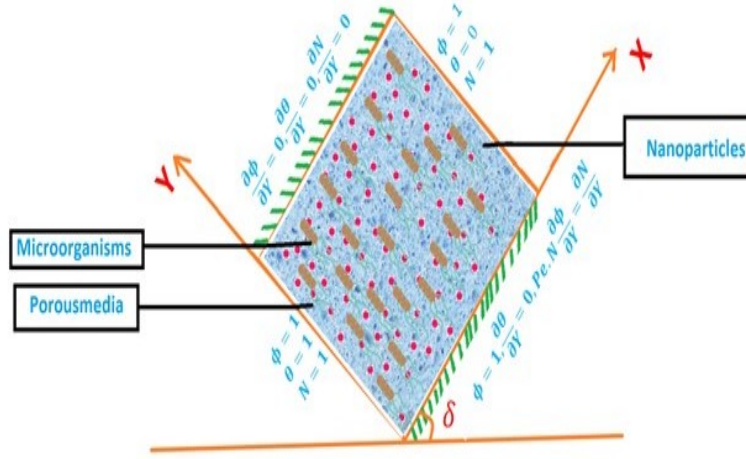


Figure 1: Physical geometry and coordinate system.

The average quantities of Nusselt number, nanoparticle Sherwood number, and microorganism Sherwood number is defined as

$$\begin{aligned} Nu_{avg} &= \int_0^1 Nu_Y dY, \\ Sh_{avg} &= \int_0^1 Sh_Y dY, \\ Nn_{avg} &= \int_0^1 Nn_Y dY. \end{aligned}$$

3 Numerical method

To find the numerical solution to (8)–(11), partial differential equations with boundary conditions Galerkin's weighted residuals finite element method are solved with the help of MATLAB [9]. In this method, a two-dimensional field is divided into small triangular parts, in which each part is named an element. Over each element, assume a piecewise trial function.

Let Ψ , θ , ϕ , and N be approximated by $\Psi = \sum_{i=1}^3 \Psi_i \xi_i$, $\theta = \sum_{i=1}^3 \theta_i \xi_i$, $\phi = \sum_{i=1}^3 \phi_i \xi_i$, and $N = \sum_{i=1}^3 N_i \xi_i$, where ξ_i is the linear interpolating functions over each triangular element. The FEM model matrix is as follows:

$$\begin{bmatrix} [L^{11}] & [L^{12}] & [L^{13}] & [L^{14}] \\ [L^{21}] & [L^{22}] & [L^{23}] & [L^{24}] \\ [L^{31}] & [L^{32}] & [L^{33}] & [L^{34}] \\ [L^{41}] & [L^{42}] & [L^{43}] & [L^{44}] \end{bmatrix} \begin{bmatrix} \{\Psi\} \\ \{T\} \\ \{C\} \\ \{N\} \end{bmatrix} = \begin{bmatrix} \{M^1\} \\ \{M^2\} \\ \{M^3\} \\ \{M^4\} \end{bmatrix},$$

where

$$L^{11} = \iint_{\Omega_e} \left[\frac{\partial \xi_j}{\partial X} \frac{\partial \xi_i}{\partial X} + \frac{\partial \xi_j}{\partial Y} \frac{\partial \xi_i}{\partial Y} \right] dx dy,$$

$$\begin{aligned}
L^{12} &= -Ra \iint_{\Omega_e} (\xi_j \frac{\partial \xi_i}{\partial X} \cos \delta - \xi_j \frac{\partial \xi_i}{\partial Y} \sin \delta) dX dY, \\
L^{13} &= RaNr \iint_{\Omega_e} (\xi_j \frac{\partial \xi_i}{\partial X} \cos \delta - \xi_j \frac{\partial \xi_i}{\partial Y} \sin \delta) dX dY, \\
L^{14} &= RaRb \iint_{\Omega_e} (\xi_j \frac{\partial \xi_i}{\partial X} \cos \delta - \xi_j \frac{\partial \xi_i}{\partial Y} \sin \delta) dX dY, \\
M^1 &= 0, \\
L^{21} &= 0, \\
L^{22} &= \iint_{\Omega_e} [\frac{\partial \Psi}{\partial Y} \xi_j \frac{\partial \xi_i}{\partial X} - \frac{\partial \Psi}{\partial X} \xi_j \frac{\partial \xi_i}{\partial Y} + \frac{\partial \xi_i}{\partial X} \frac{\partial \xi_j}{\partial X} + \frac{\partial \xi_i}{\partial Y} \frac{\partial \xi_j}{\partial Y} - Nt(\frac{\partial \theta}{\partial X} \xi_j \frac{\partial \xi_i}{\partial X} + \frac{\partial \theta}{\partial Y} \xi_j \frac{\partial \xi_i}{\partial Y})] dX dY, \\
L^{23} &= -Nb \iint_{\Omega_e} [\frac{\partial \theta}{\partial X} \xi_j \frac{\partial \xi_i}{\partial X} + \frac{\partial \theta}{\partial Y} \xi_j \frac{\partial \xi_i}{\partial Y}] dX dY, \\
L^{24} &= 0, M^2 = 0, \\
L^{31} &= 0, \\
L^{32} &= -\frac{Nt}{Nb} \iint_{\Omega_e} [\frac{\partial \xi_i}{\partial X} \frac{\partial \xi_j}{\partial X} + \frac{\partial \xi_i}{\partial Y} \frac{\partial \xi_j}{\partial Y}] dX dY, \\
L^{33} &= \iint_{\Omega_e} [Le \left(\frac{\partial \Psi}{\partial Y} \frac{\partial \phi}{\partial X} - \frac{\partial \Psi}{\partial X} \frac{\partial \phi}{\partial Y} \right) + \frac{\partial \xi_i}{\partial X} \frac{\partial \xi_j}{\partial X} + \frac{\partial \xi_i}{\partial Y} \frac{\partial \xi_j}{\partial Y}] dX dY, \\
L^{34} &= 0, M^3 = 0, \\
L^{41} &= 0, L^{42} = 0, \\
L^{43} &= \iint_{\Omega_e} \frac{PePr}{Sc} (\frac{\partial \xi_i}{\partial X} \frac{\partial \xi_j}{\partial X} + \frac{\partial \xi_i}{\partial Y} \frac{\partial \xi_j}{\partial Y}) dX dY, \\
L^{44} &= \iint_{\Omega_e} [\frac{\partial \Psi}{\partial Y} \xi_j \frac{\partial \xi_i}{\partial X} - \frac{\partial \Psi}{\partial X} \xi_j \frac{\partial \xi_i}{\partial Y} + \frac{Pr}{Sc} (\frac{\partial \xi_i}{\partial X} \frac{\partial \xi_j}{\partial X} + \frac{\partial \xi_i}{\partial Y} \frac{\partial \xi_j}{\partial Y})] dX dY, \\
M^4 &= 0.
\end{aligned}$$

To linearize the system of equations, the functions are incorporated, which are assumed to be known. After applying the boundary conditions, a matrix of system of linear equations is formed, which is solved by using the Gauss-Seidel iteration method. The convergence of the solution is assumed when the relative error for each variable between two consecutive iterations is observed below the convergence criteria such that $|\psi^{n+1} - \psi^n| \leq 10^{-5}$, where n is the number of iterations and ψ stands for Ψ, θ, C .

To choose the grid size, the grid independence test is performed for $21 \times 21, 41 \times 41, 61 \times 61, 71 \times 71, 81 \times 81, 91 \times 91$ grid sizes. The grid independence test reveals that the grid size 81×81 is sufficient to study in the the bioconvection phenomena.

Table 1: Accuracy test of mean Nusselt numbers with the literature.

Authors	$Ra = 10$	$Ra = 100$	$Ra = 1000$
Varol, Oztop, and Pop [33]	-	-	13.564
Cross, Bear, and Hickox [12]	-	-	13.470
Manole [22]	-	3.118	13.637
Sheremet and Pop [28]	1.079	3.115	13.667
Present results	1.081	3.1271	13.715

4 Result and discussion

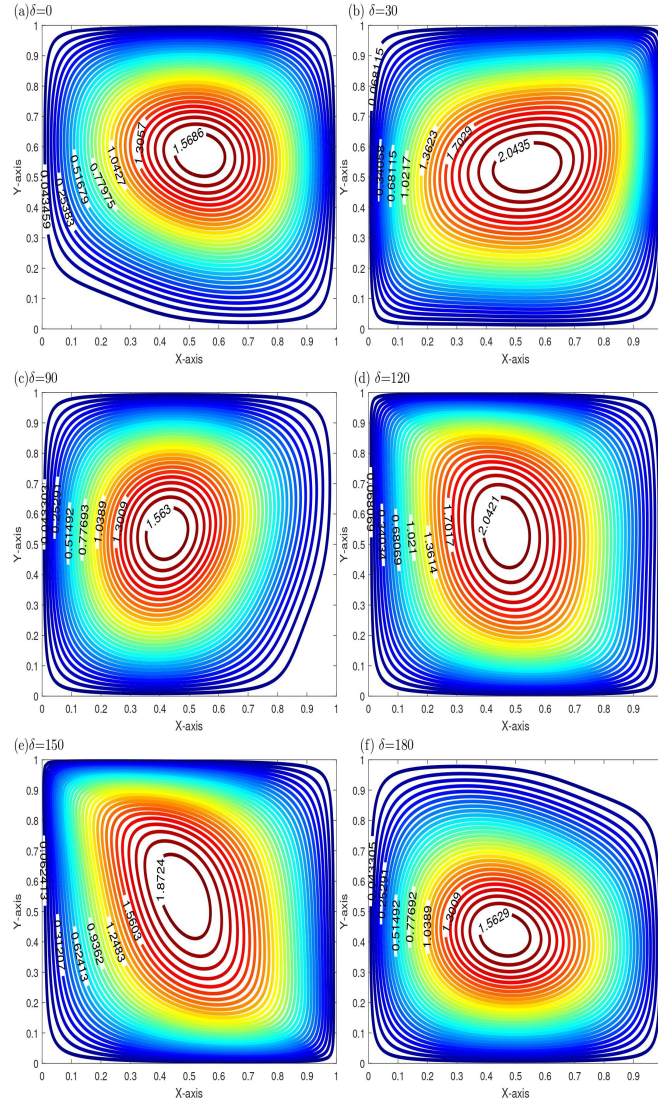
The present equations (8)–(11) are numerically investigated and analyzed in the porous square cavity filled with nanofluid and gyrotactic microorganisms at different inclination angles. The numerical investigation is carried out with the following parameters considered Rayleigh number ($Ra = 25$), bioconvection Rayleigh number ($Rb = 15$), Lewis number ($Le = 1$), Peclet number, thermophoresis parameter, Brownian parameter, buoyancy ratio parameter, Schmidt number 0.1, Prandtl number 6.9, and inclination angle ($\delta = 30^\circ$) unless when it is mentioned. Streamlines are presented in Figure 2 for various values of inclination angle (δ). When $\delta = 0^\circ$, the cells moved in the clockwise direction in the square enclosure. The absolute maximum of the stream function is $|\Psi_{\max}| = 1.56$. At 30° , inclination angle the maximum stream function value is $|\Psi_{\max}| = 2.0435$, and the rotation of the cell moves in the same direction. The inclination angle increased to 90° , and the velocity of the fluid flow is reduced. At 120° , the intensity of the flow increased to $|\Psi_{\max}| = 2.0421$. In this, the cell moves to the center regime with the intensity of the gravitational force. At 150° inclination angle, the flow strength is low and the cell moves near to corners of the left down wall and right top walls. At 180° , the fluid flow velocity is less with the strength of cell $|\Psi_{\max}| = 1.5629$.

Isotherms are demonstrated in Figure 3 for various inclination angles from 0° to 180° . At inclination 30° , the temperature distribution is indicating the stratified diagonally. At 180° , isotherms are parallel to the vertical walls, which shows the transfer of heat in the mode of heat conduction.

Nanoparticle isoconcentrations of the fluid for various angles are expressed in Figure 4. At 0° to 30° inclination angle, the nanoparticle volume fraction was raised near the bottom cavity wall. When the square enclosure was moved from angle 90° to 120° , the nanoparticle isoconcentration decreased. When the angle is 120° to 150° , again the concentration of nanoparticles increases. When the angle of inclination is inclined from 150° to 180° , the concentration of nanoparticles is decreased. In these all angles, the cell is divided into two different parts: one is formed near the bottom adiabatic wall and the other part is formed as a semi-opened vertex close to the top adiabatic wall.

Figure 5 displays isoconcentrations of microorganisms for the various inclination angles. At 0° to 30° inclination angle, two types of cells are formed: one cell is near the bottom adiabatic wall and the cell moves from the cold wall to the hot wall, the second is an open semi vertex formed at the top cavity wall, and it moves from the hot wall to the cold wall. When the inclination varies from 0° to 180° , the movement of cells in the isoconcentrations of microorganisms and nanoparticle volume fraction is the same. The concentration of microorganisms' maximum value is found at $\delta = 30^\circ, 120^\circ$.

In Figure 6, the effect of Rb and Nt on average Nusselt number, Sherwood numbers of nanoparticles, and Sherwood number of microorganisms is

Figure 2: Streamlines for the inclination angle $\delta = 0^\circ - 180^\circ$

discussed. Moreover, Rb increases Nu_{avg} and Sh_{avg} from $0^\circ \leq \delta \leq 90^\circ$, $90^\circ \leq \delta \leq 180^\circ$, and it reaches high. Indeed, at 0° , 90° , and 180° the average Nusselt number and average Sherwood number values are low. Also, Rb increases Nn_{avg} from 0° to 180° . In addition, Nt increases Nu_{avg} from 0° to

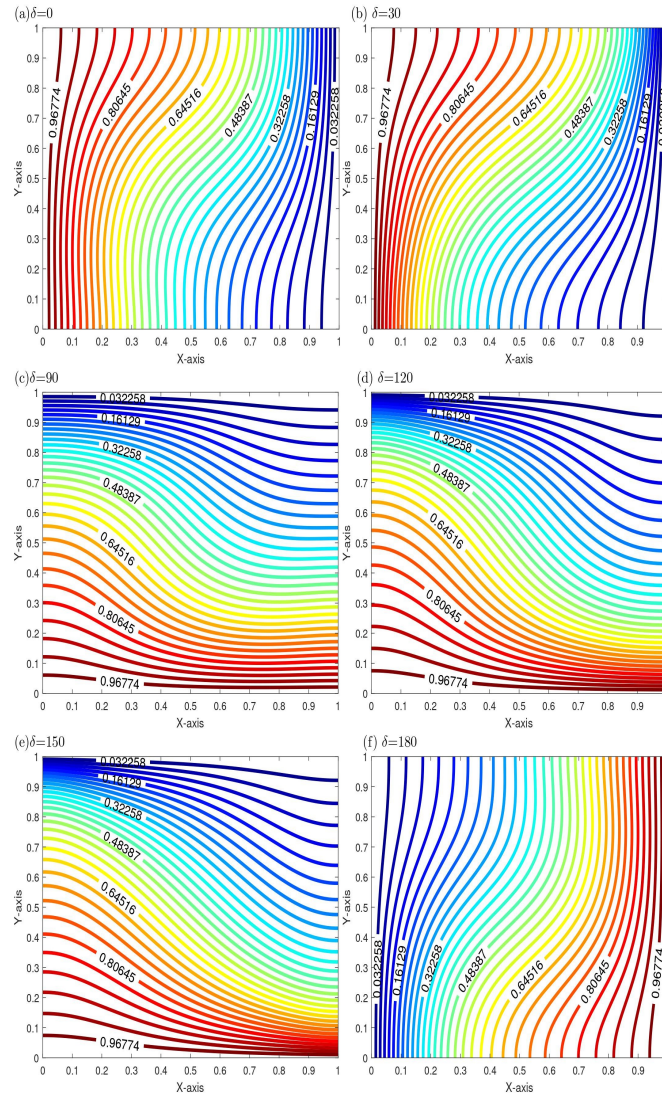


Figure 3: Isotherms for the inclination angle $\delta = 0^\circ - 180^\circ$

180° , and it shows wavy behavior, and Sh_{avg} and Nn_{avg} are also increased with the increase of thermophoresis parameter.

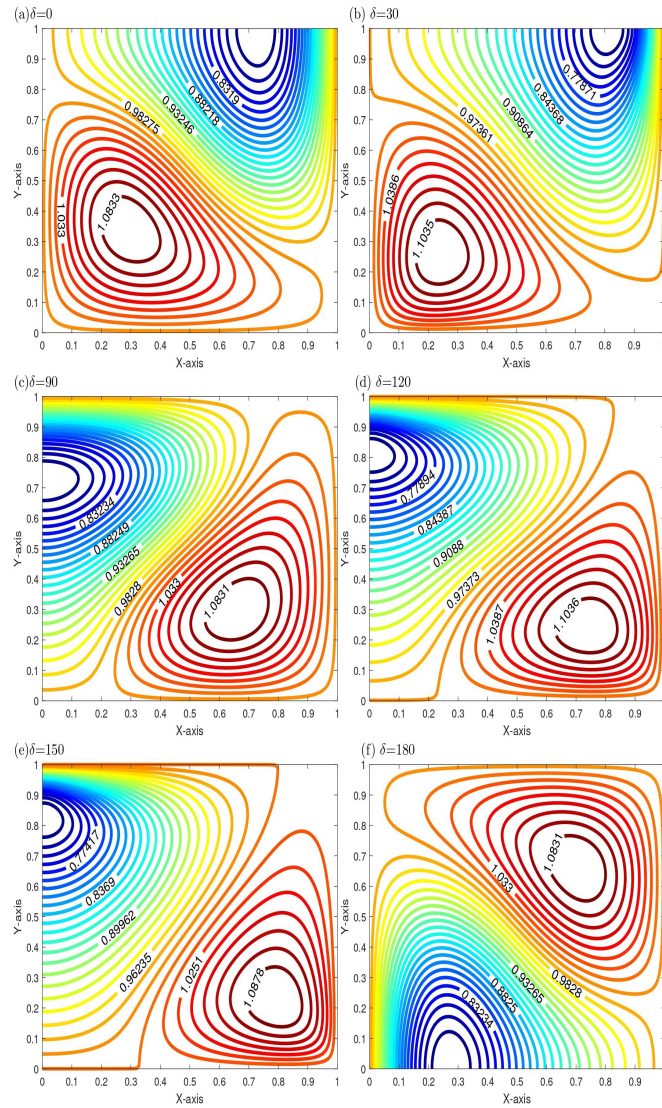
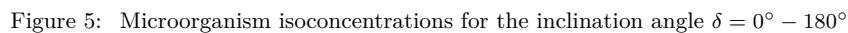


Figure 4: Isoconcentration of nanoparticle volume fraction for the inclination angle $\delta = 0^\circ - 180^\circ$

5 Conclusion

The effect of porous square cavity inclination with the horizontal surface with nanofluid and gyrotactic microorganisms was analyzed with the streamlines,



1. The velocity of the nanofluid flow is high at the angle 30° , 120° and in the remaining angles, the flow intensity is low.

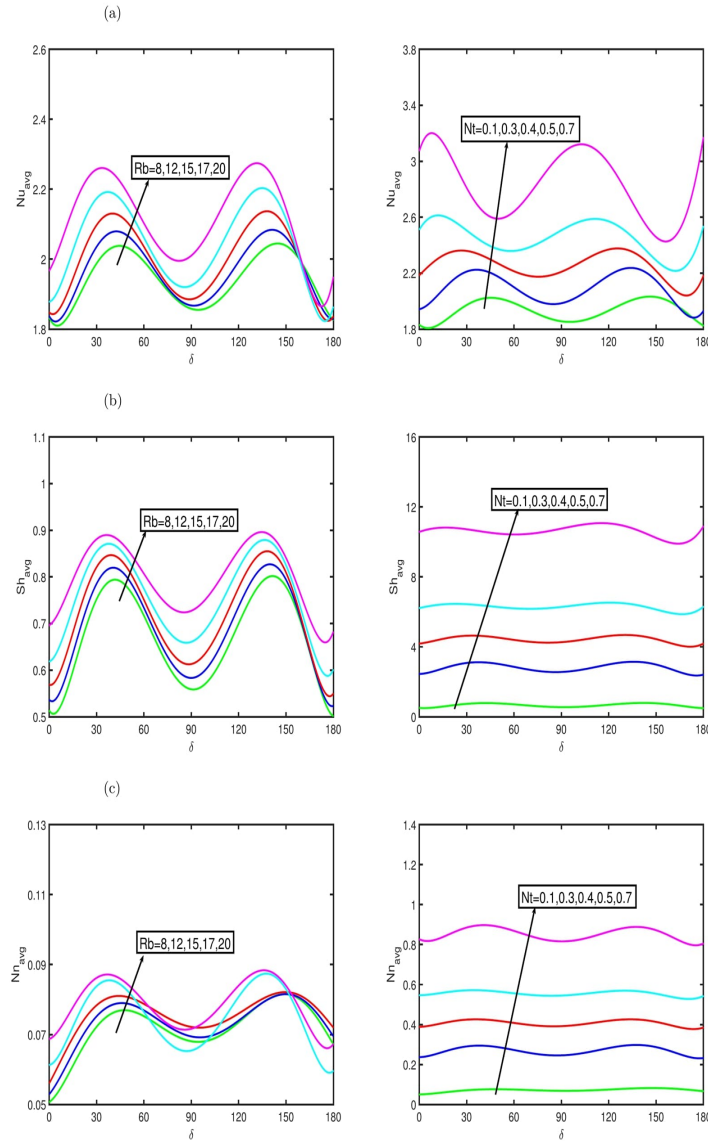


Figure 6: Representation of (a) Average Nusselt number (b) Average nanoparticle Sherwood number (c) Average Microorganism Sherwood number for angle versus Rb and angle versus Nt

2. The temperature distribution of the nanofluid is affected by the square cavity inclination.

3. Nanoparticle isoconcentration and microorganism isoconcentrations are high at the 30° and 120° , and at the remaining angles, the value is low.

4. Thermophoresis parameter increases Nu_{avg} , Sh_{avg} , and Nn_{avg} from $0^\circ \leq \delta \leq 180^\circ$. Also, Nt increases Nu_{avg} from $0^\circ \leq \delta \leq 180^\circ$, but at 0° and 180° , the value is low. 5. Bioconvection Rayleigh number increases Nu_{avg} , Sh_{avg} , and Nn_{avg} .

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